BTeV: Detector, R&D, Project Organization, Cost and Schedule

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Talk presented to P5

March 26, 2003

Outline

- Review of the BTeV Detector
- Technical Status and R&D Program
- Project Organization
- Cost estimate
- Schedule
- Operational Considerations
- Summary

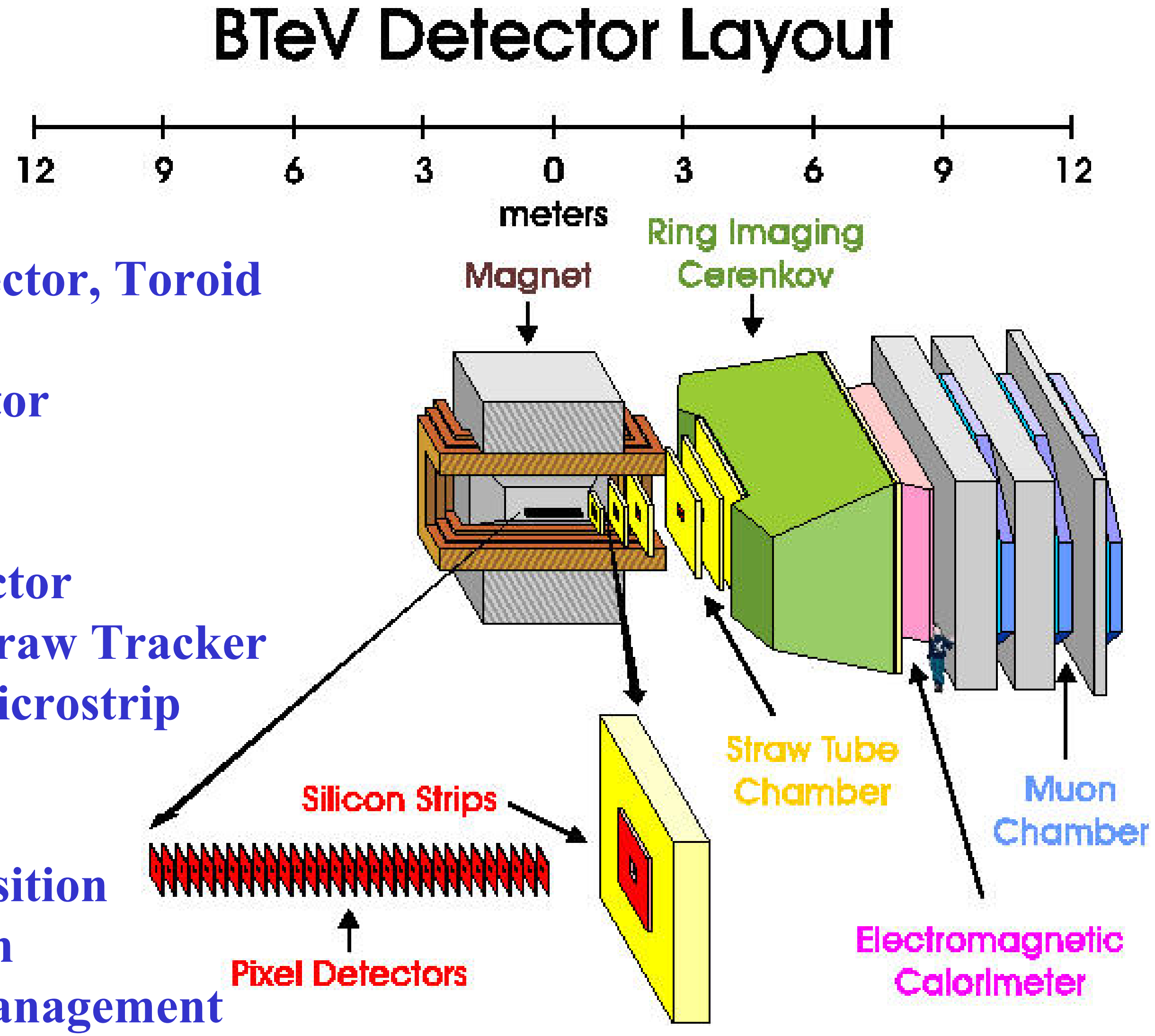
Key Design Features of BTeV

- A **dipole located ON the IR gives BTeV a spectrometer covering the forward antiproton rapidity region.**
- A precision vertex detector based on **planar pixel arrays**
- A **vertex trigger at Level I** which makes BTeV especially efficient for states that have only hadrons. The tracking system design has to be tied closely to the trigger design to achieve this.
- Strong particle identification based on a **Ring Imaging Cerenkov counter.** Many states emerge from background only if this capability exists. It enables use of charged kaon tagging.
- **A lead tungstate electromagnetic calorimeter for photon and π^0 reconstruction.**
- A very **high capacity data acquisition system** which frees us from making excessively restrictive choices at the trigger level

½ key measurements in B_s and ½ have γ's

Work Breakdown Structure

1.1 Vertex Detector, Toroid and Beam Pipe
1.2 Pixel Detector
1.3 RICH
1.4 EMCAL
1.5 Muon Detector
1.6 Forward Straw Tracker
1.7 Forward Microstrip tracker
1.8 Trigger
1.9 Data Acquisition
1.10 Integration
1.11 Project Management



Technical Status

- **Our basic design has been stable since the original proposal in May 2000.**
- The major issue over which we were unsure is now resolved: we will not use an aerogel radiator but a liquid radiator for the low momentum particle ID
- We have eliminated three major criticisms:
  - **We will use commercial networking equipment in the DAQ rather than building a custom switch**
  - **We have received through the NSF, the funding required to develop a fault-tolerant, fault-adaptive, software system for the trigger farm**
  - **We have removed all water-vacuum joints in the pixel detector cooling system in favor of thermopyrolitic graphite cold fingers**
- **No "gotcha"s. Many "plans" in 2000 are well on their way to realization today.**
- Options in the area of sensors for RICH (HPD vs MAPMT), some optimization issues for forward tracker, choice of processors for trigger.

Experiment R&D

- The creation of a new experiment is now almost always a big task
  - **At a mature machine, you are improving your reach by doing much harder experiments which may require**
    - **running at much higher luminosity**
    - **achieving much higher background rejection**
  - **For BTeV this meant developing new kinds of detectors, triggers, computing techniques, etc**

We have had a very efficient, successful R&D program which has or will soon demonstrate all the key detector, trigger and data acquisition techniques.

Key support by DOE/FNAL, DOE/University Program, NSF, INFN, IHEP, and others. RTES project supported by a $5M Information Technology Research (ITR) grant from the NSF.

BTeV R&D Highlights and Plans

- **Pixel Detector:** achieved design (5-10 micron) resolution in 1999 FNAL test beam run. Demonstrated radiation hardness in exposures at IUCF. The final readout chip has been bench tested and will undergo final testing in FNAL test-beam in 2003
- **Straw Detector:** prototype built, to be tested at FNAL in 2003
- **EMCAL:** four runs at IHEP/Protvino demonstrated resolution and radiation hardness,and effectiveness of calibration system. A fifth test will occur in April.
- **RICH:** HPD developed and has been bench tested. FE electronics prototype developed for HPD's. FE electronics for MAPMT option being developed Full test cell under development for beam test at FNAL in 2003
- **Muon system** tested in 1999 FNAL test beam run. Better shielding from noise implemented and bench-tested. Design to be finalized in FNAL test- beam in 2002
- **Silicon strip** electrical and mechanical design well underway
- **Trigger code** implemented on FPGA, Prototypes being constructed. NSF/RTES project to write fault tolerant software for massively parallel systems is well-along

Pixel Vertex Detector

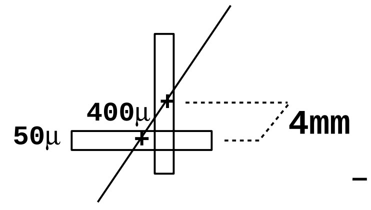
Reasons for Pixel Detector:

- Superior signal to noise
- Excellent spatial resolution -- 5-10 microns depending on angle, etc
- Very low occupancy
- Very fast
- Radiation hard

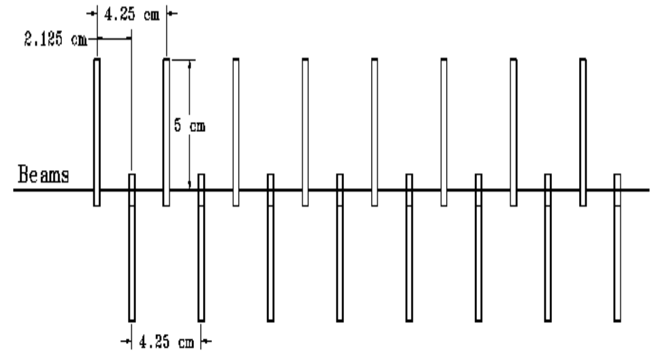
Special features:

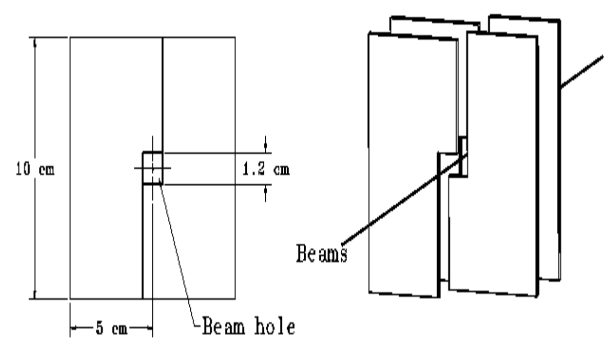
- It is used directly in the Level 1 trigger
- Pulse height is measured on every channel with a 3 bit FADC
- It is inside a dipole and gives a crude standalone momentum

The BTeV Baseline Pixel Detector



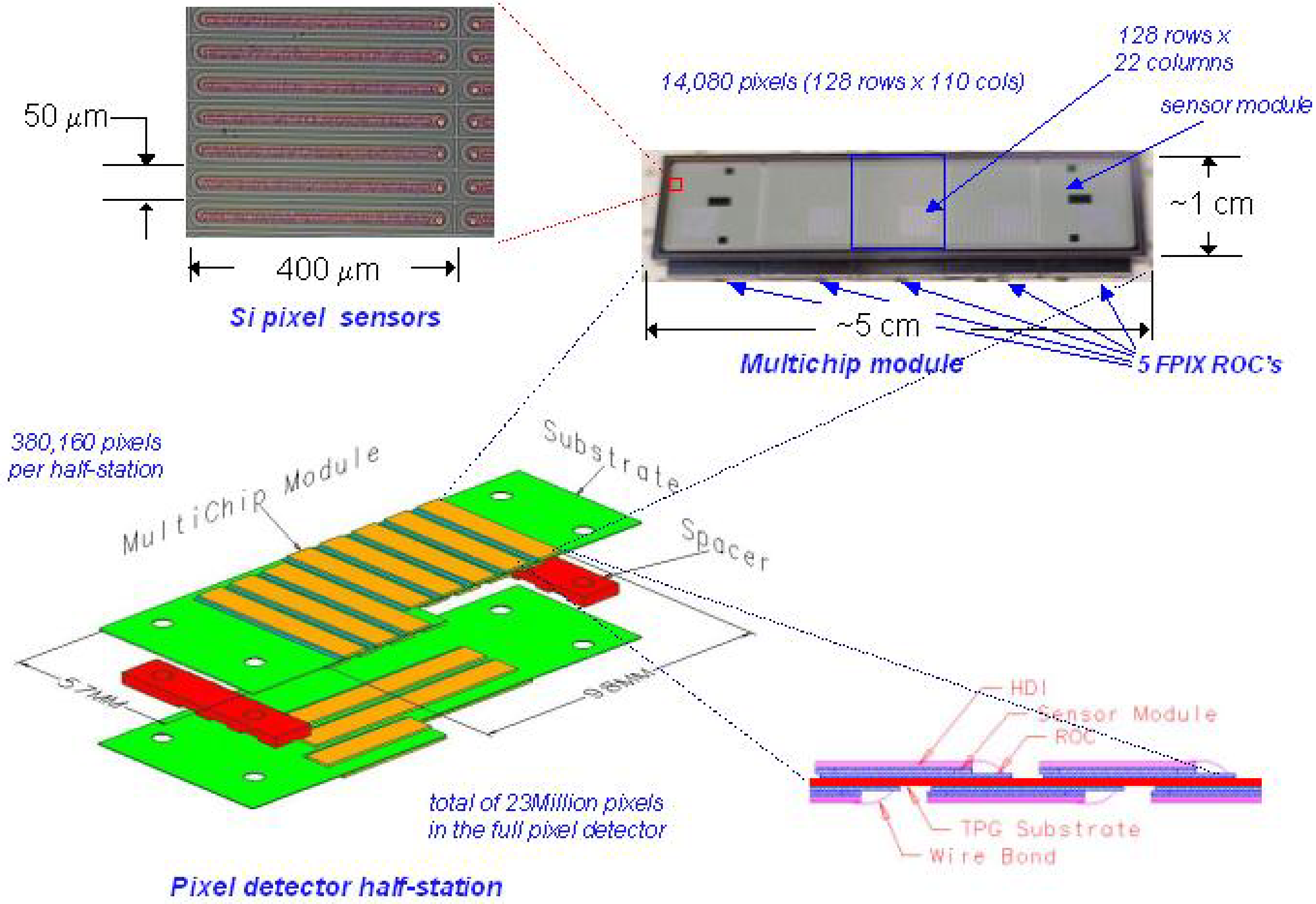
Pixel Orier





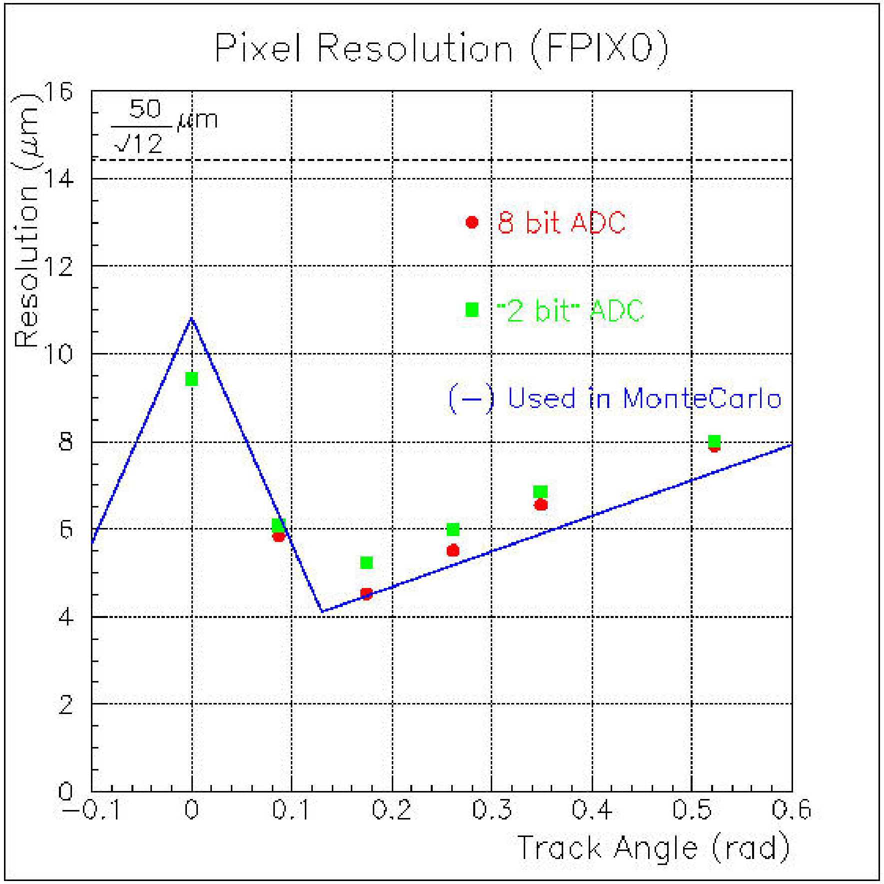
Readout Chip

Half-Station Assembly



Pixel Detector Resolution

Pixel Resolution vs angle of track as measured in the FNAL test beam. Inclined tracks cross pixel boundaries. Resolution requirements for BTeV are met with 3 bit ADC readout.



Vacuum and Cooling System

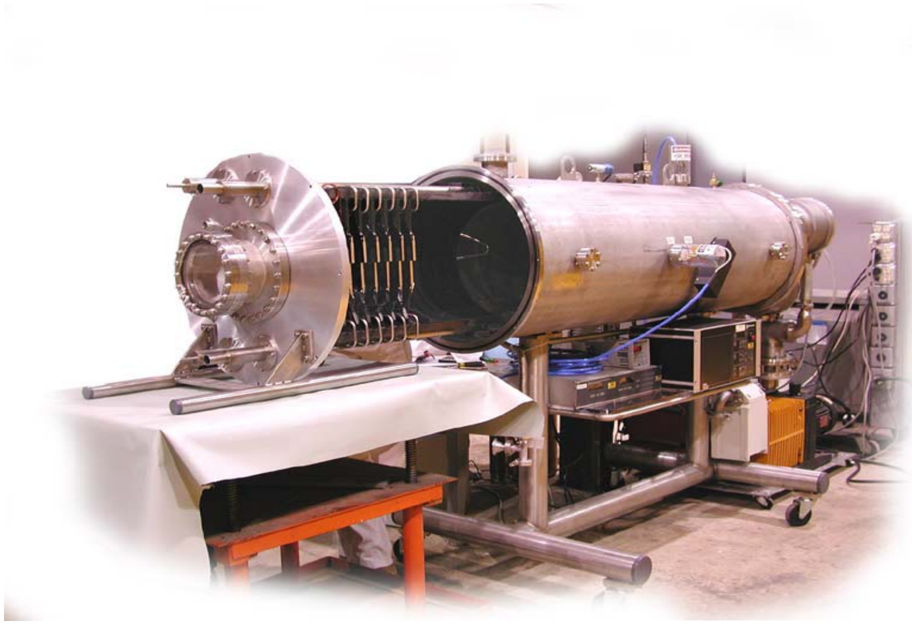
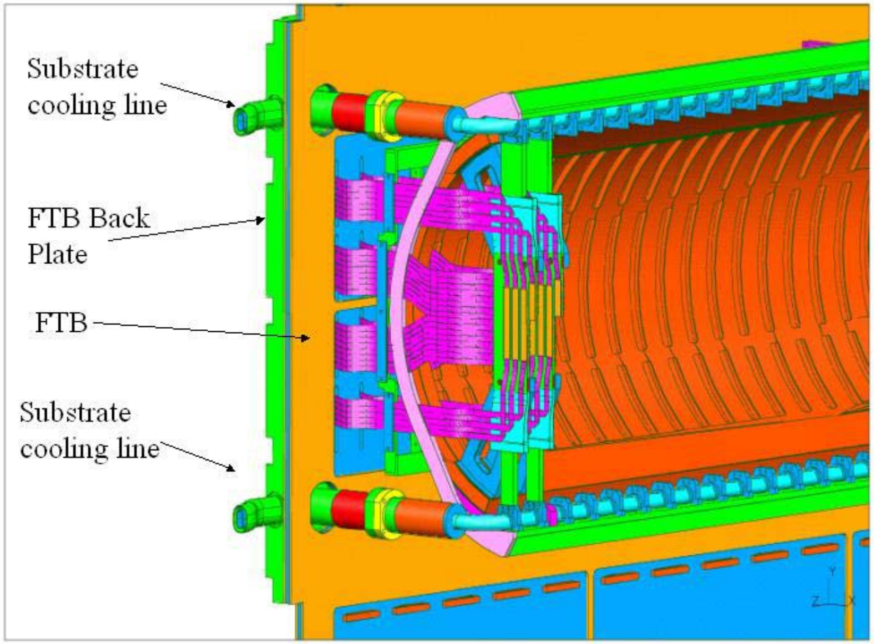


Fig. 4: Photo of the prototype of the vacuum system for the silicon pixel detector



Forward Tracker

Table 4.4: Properties of the baseline forward straw tracker (1 arm)

Property	Value
Straw size	4 mm diameter
Central hole	27 cm × 27 cm
Total Stations	7
Z positions (cm)	95, 138, 196, 288, 332, 382, 725
Half size (cm)	27, 41, 61, 88, 102, 116, 204
Views per station	3 (X,U,V)
Layers per view	3
Total number of straws	29,088
Total station thickness	0.6% X_0
Total channels	58,176
Readout	ASD + timing chip (6 bits), sparsified

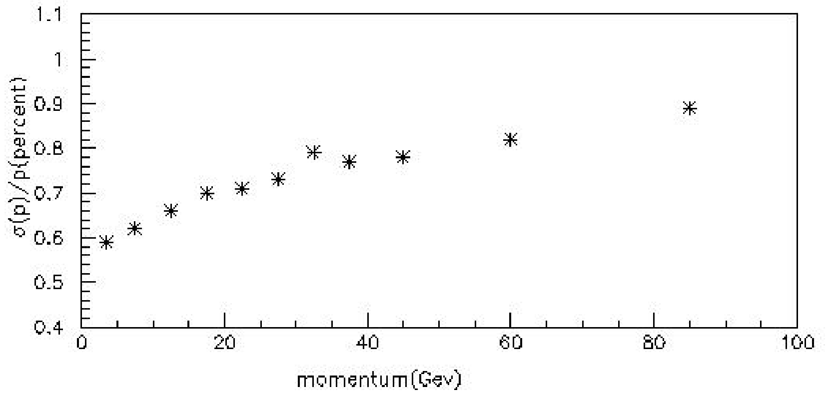
4mm diameter straws
At Large angles (low occupancy)

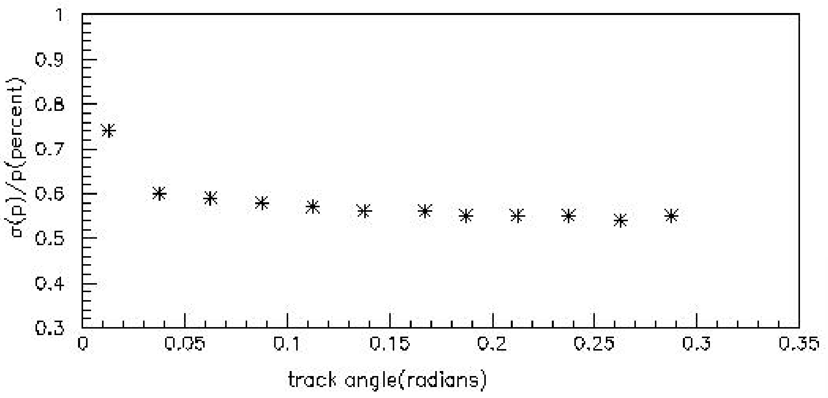
Table 4.5: Properties of the baseline forward silicon tracker (1 arm)

Property	Value
Si-sensors	$\sim 7 \times 7$ cm^2, p-on-n type
Pitch	100 μm
Thickness	200 μm
Sensor configuration	4 ladders of 4 sensors
Coverage	27cm × 27cm
Central hole	5.4 cm × 5.4 cm (7 cm × 7 cm in last station)
Total stations	7
Z positions (cm)	99, 142, 200, 292, 336, 386, 729
Views per station	3 (X, U, V)
Channels per view	~5,600
Total channels	~127,600
Readout	sparsified binary

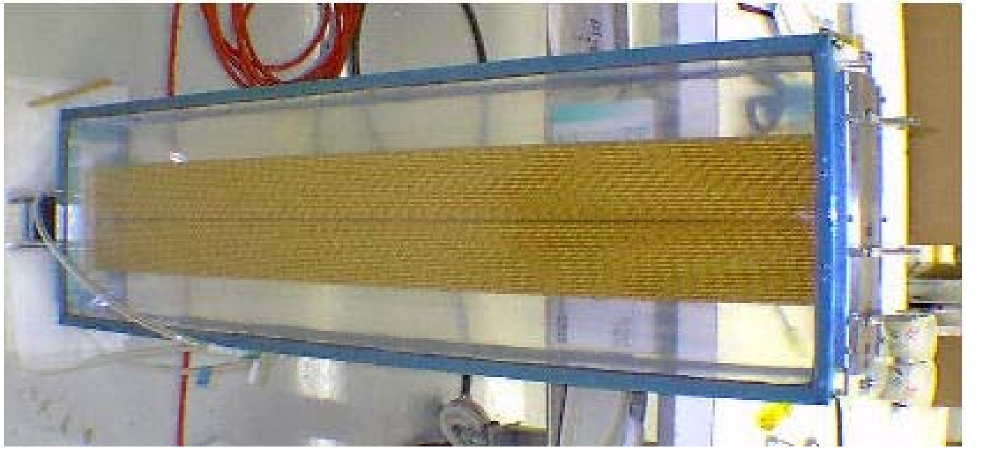
100 μm Strips at
Small angles (high occupancy)

Forward Tracker





Predicted performance - Momentum resolution better than 1% over full momentum and angle range



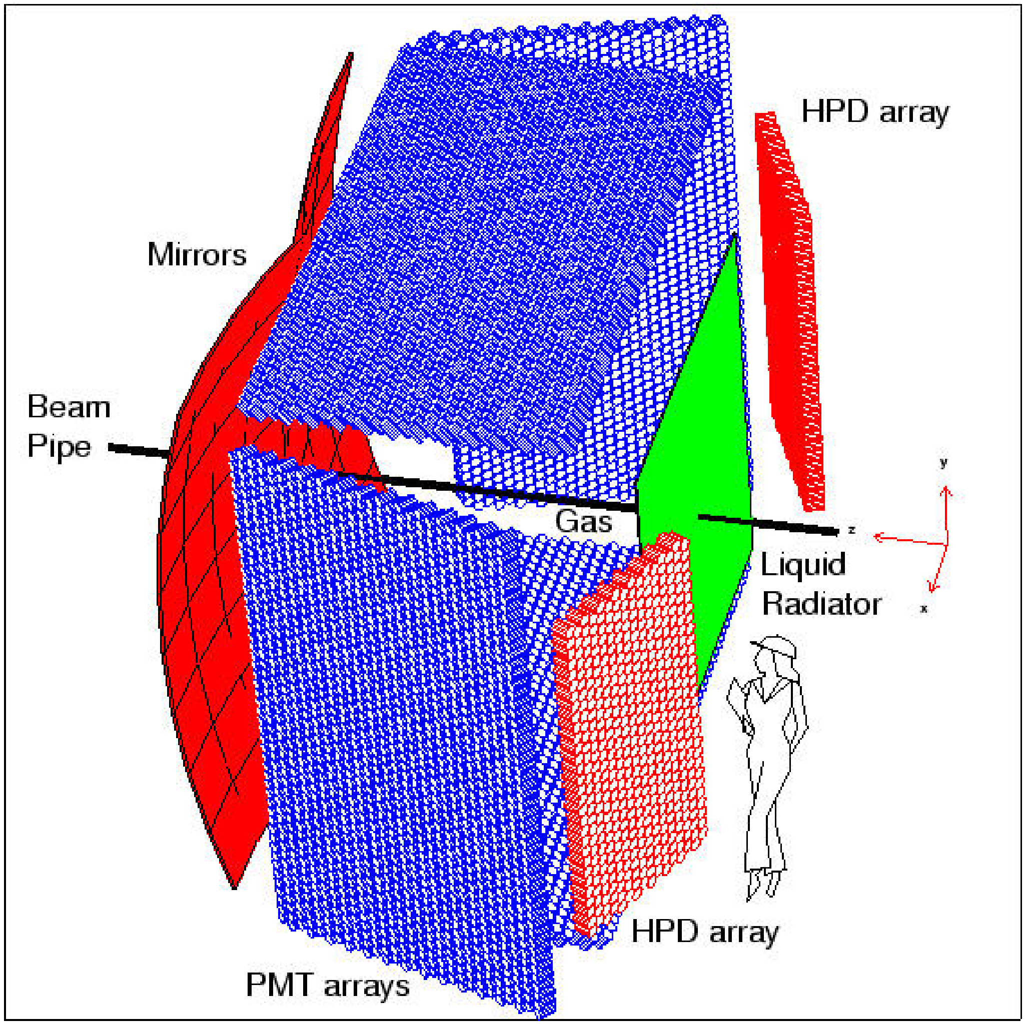
Prototype Straw tracker being constructed for FNAL beam test summer/fall 2002

Drawing Of forward Microstrip tracker

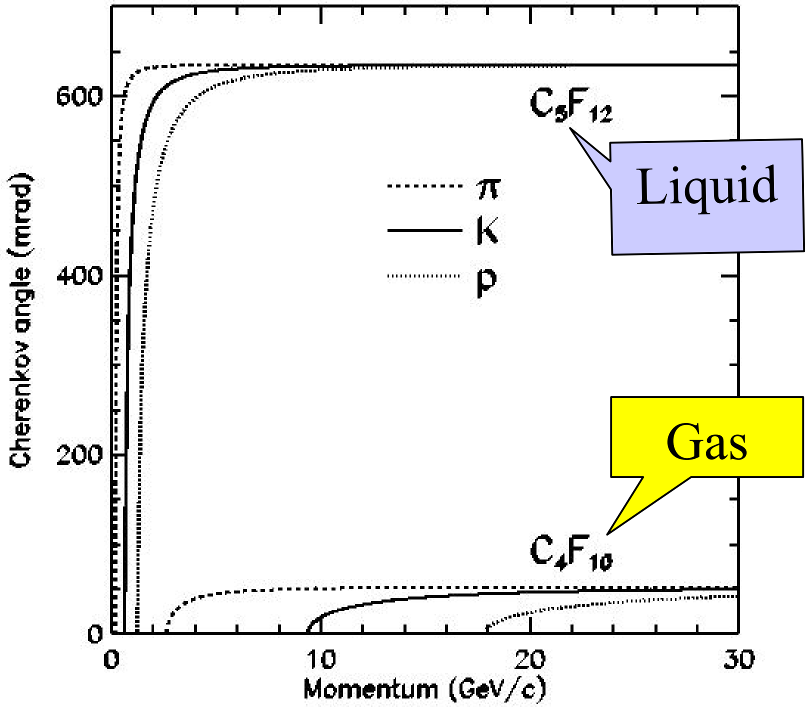
Ring Imaging Cherenkov Counter

- **Original system had a gas radiator, C_4F_{10}, and an aerogel radiator, both detected on the same planes of Hybrid PhotoDiodes.**
- **The gas section has plenty of photons and is turning out to be straightforward to implement**
- **The aerogel was proven to be inadequate. It has too few photons distributed in large, diffuse rings which get tangled up in the more intense rings from the gas section. Aerogel thickness is limited by scattering by bubbles**
- **Without the aerogel, we lack K/p discrimination below 9 GeV, which especially impacts our "kaon" tagging.**
- **We have replaced the aerogel with a liquid, C_5F_{12}, which makes more photons and at very large angles. These are detected on a new array of PMTs on the sides of the gas vessel. With more photons, and separated readout, the problems are solved**

Layout of the New Particle Identifier showing the liquid radiator and its PMTs

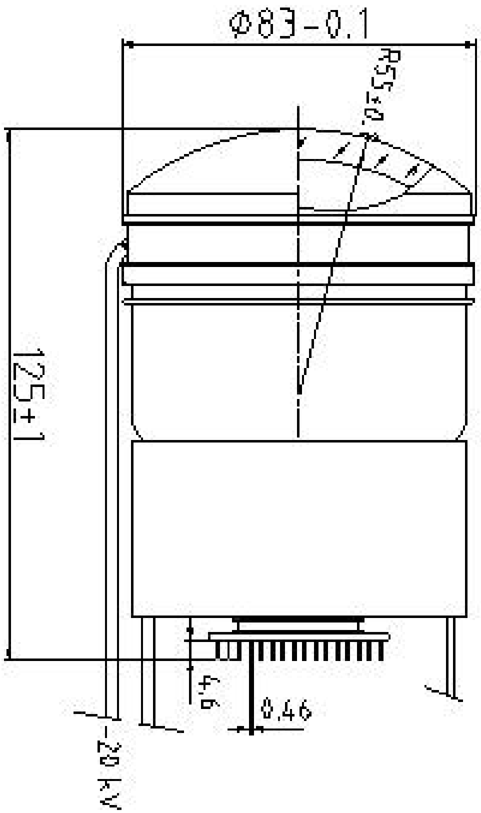


Cherenkov angle vs P

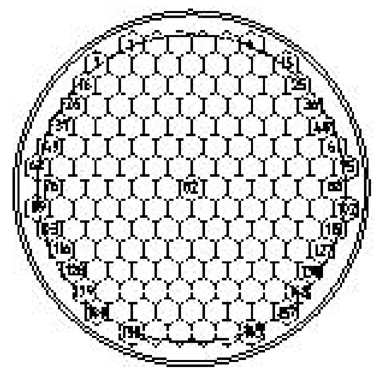


HPD Schematic

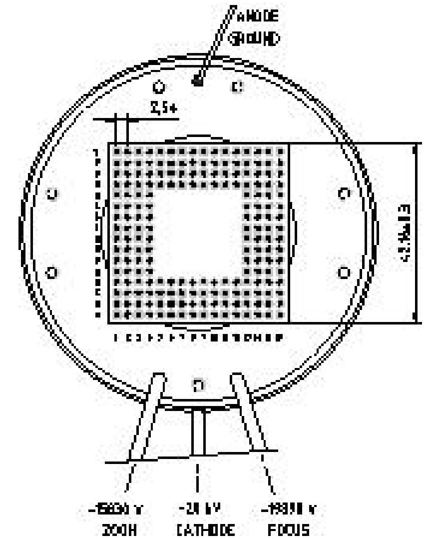
HPD Tube

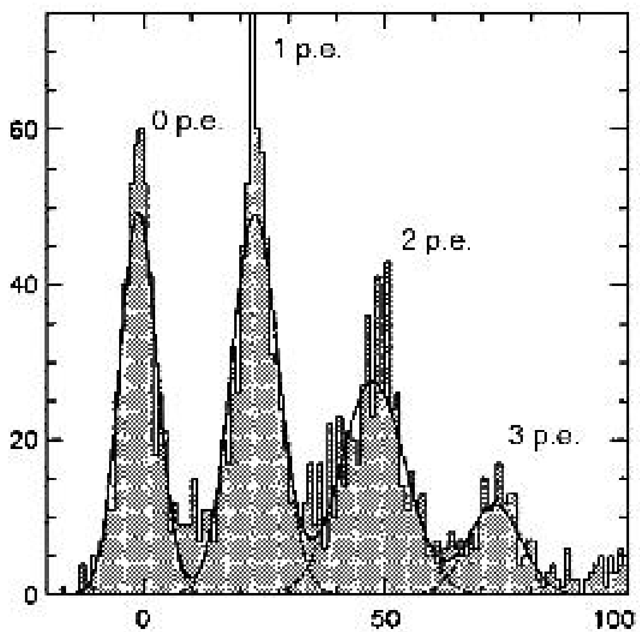


HPD Pixel array



HPD Pinout





Pulse Height from 163 pixel prototype HPD. Note pedestal, 1, 2, 3 pe peaks

MultiAnode PMT (MAPMT) Option

Multi-anode PMT

1″ x 1″

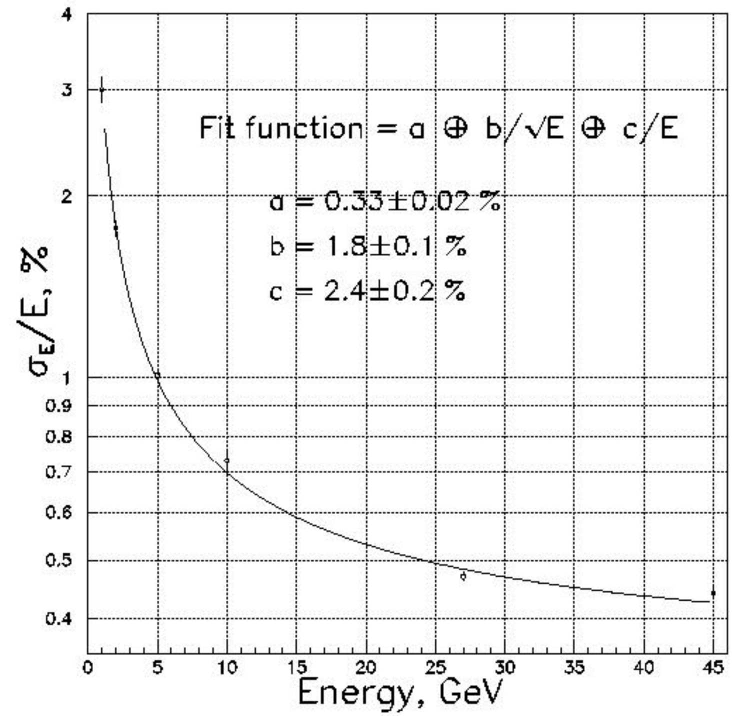
Electromagnetic Calorimeter

Table 4.8: Properties of $PbWO_4$

Property	Value
Density (g/cm^3)	8.28
Radiation Length (cm)	0.89
Interaction Length (cm)	22.4
Light Decay Time (ns):	5(39%) 15(60%) 100(1%)
Refractive Index	2.30
Maximum of emission (nm)	440
Temperature Coefficient (%/°C)	-2
Light output/NaI(Tl) (%)	1.3
Light output (pe/MeV into a 2" PMT)	10

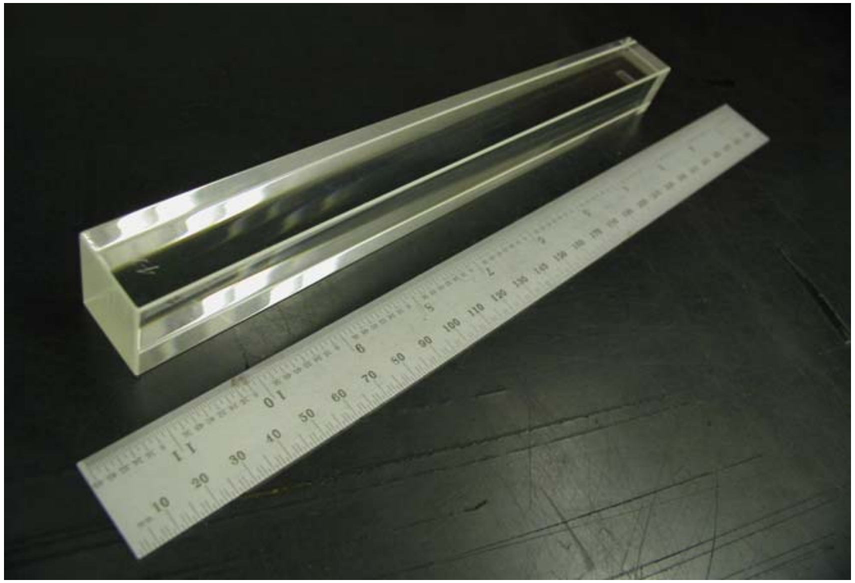
Table 4.9: Properties of the BTeV electromagnetic Calorimeter

Property	Value
transverse block size, back	28.0 mm × 28.0 mm
tapered, smaller in front	27.2 mm× 27.2 mm
Block length	22 cm
Radiation Lengths	25
Front end electronics	PMT
Digitization/readout	QIE (FNAL)
Inner Dimension	± 9.88 cm × ± 9.88 cm
Outer Radius	160 cm
Total blocks per arm	10500

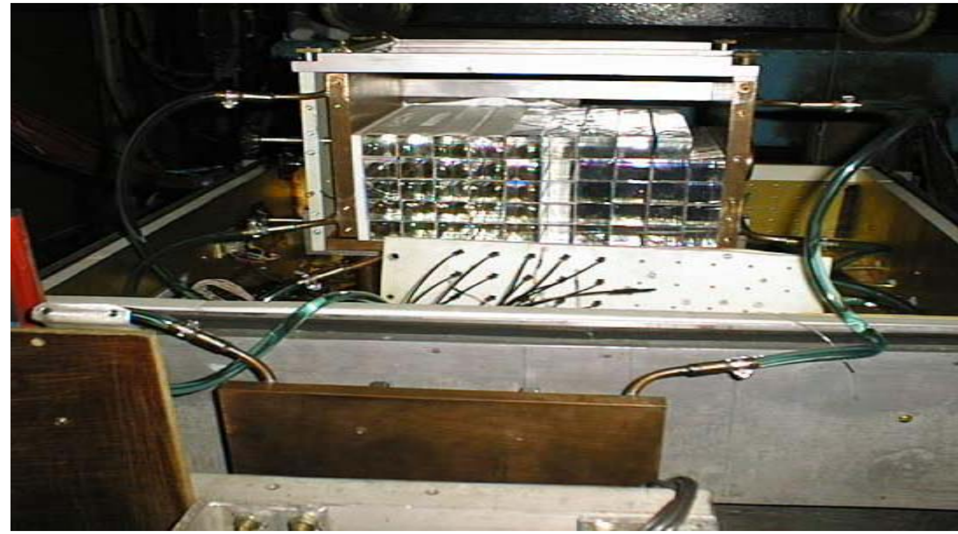


Resolution as measured in Test beam at IHEP/Protvino.
Stochastic term = 1.8%
→ σ_{π^0}~3 MeV!

Lead Tungstate Electromagnetic Calorimeter



Crystal from China's Shanghai Institute of Ceramics

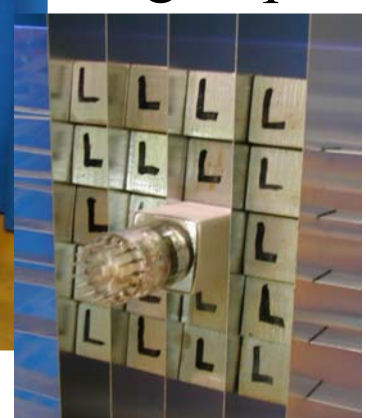


Stack of blocks from Bogoriditsk and SIC Being installed in temperature controlled box for testing at Protvino in March'02

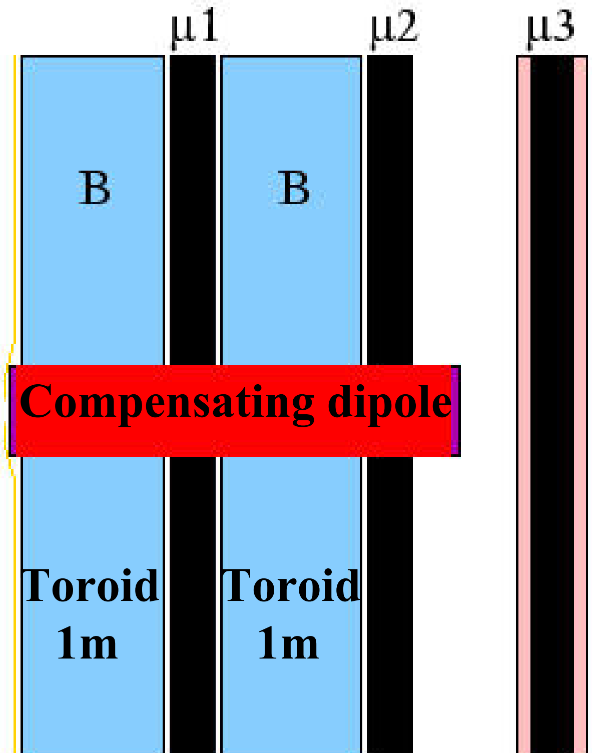
Lead Tungstate Crystals similar to CMS. Capable of excellent energy and spatial resolution. We will read them out with PHOTOMULTIPLIER tubes unlike CMS which uses avalanche photodiodes (and triodes for endcap) because of magnetic field. **BTeV achieves CLEO/BaBar/BELLE-like performance in a hadron Collider environment!**

EMCAL Stand

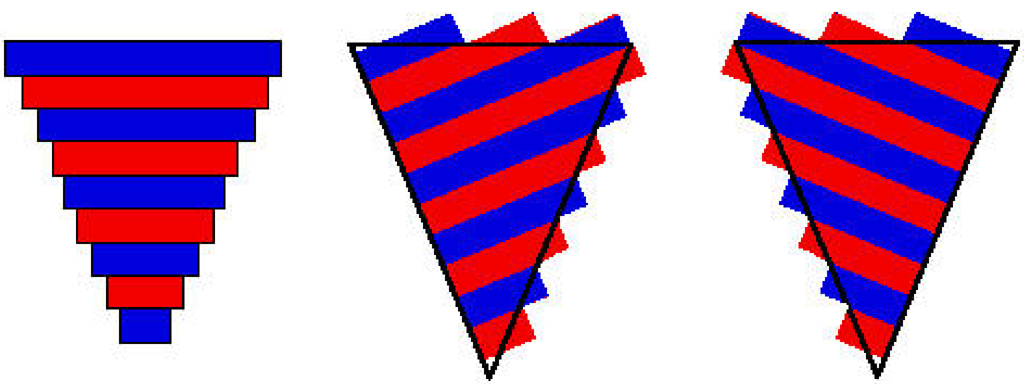
Half-height prototype of EMCAL support. Crystals can be loaded in small groups or even individually. The final support can be installed on the beam very early and crystals loaded in groups as they arrive.



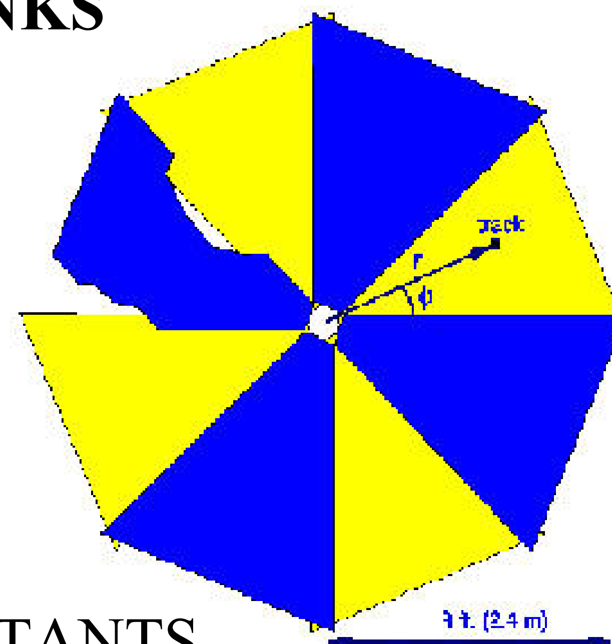
Muon Detector



PLANKS



VIEWS

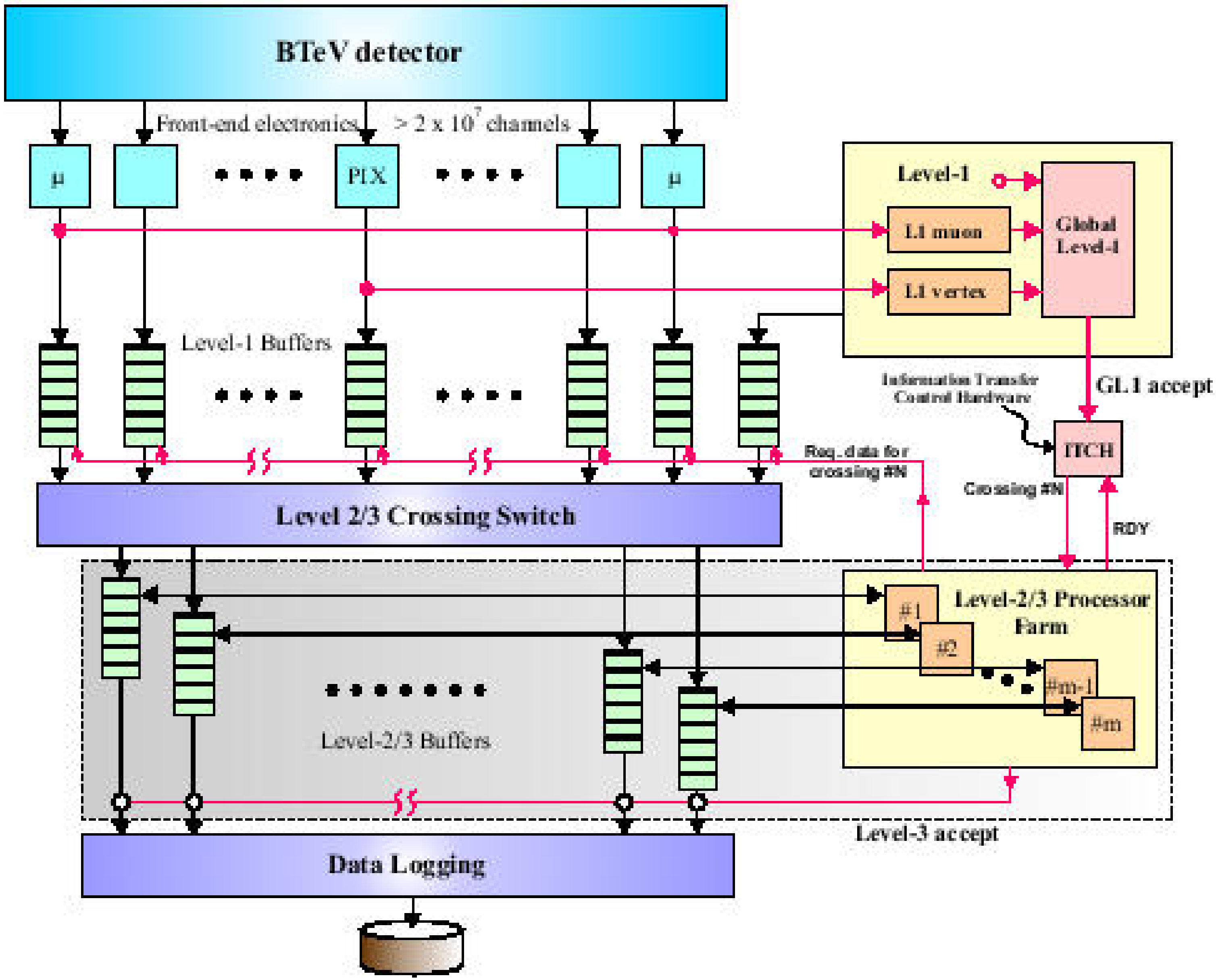


OCTANTS

Muon Installation Mockup

Mockup of Muon Detector to understand how the Octants will be installed in the toroid steel in the C0 Hall

Trigger



BTeV detector
Front-end electronics
> 2 x 10^7 channels
μ
PIX
μ
Level-1
L1 muon
L1 vertex
Global Level-1
Level-1 Buffers
Information Transfer Control Hardware
GL1 accept
ITCH
Req. data for crossing #N
Crossing #N
RDY
Level 2/3 Crossing Switch
Level-2/3 Processor Farm
#1
#2
#m-1
#m
Level-2/3 Buffers
Level-3 accept
Data Logging

The BTeV Level I Vertex Trigger

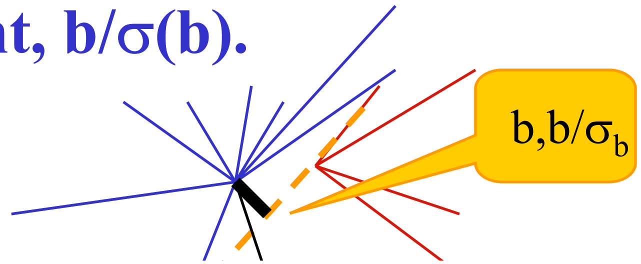
The trigger will reconstruct every beam crossing and look for TOPOLOGICAL evidence of a B decaying downstream of the primary vertex. Runs at full beam crossing rate (up to 7.6 MHz)!

- **This is made possible by a vertex detector with excellent spatial resolution, fast readout, low occupancy, and 3-d space points.**
- **A heavily pipelined and parallel processing architecture using inexpensive processing nodes optimized for specific tasks ~ 2500 processors (DSPs).**
- **Sufficient memory (~1 Terabyte) to buffer the event data while calculations are carried out.**
- **Number of conventional processors in Level 2/3 Farm is 2000**

By triggering on TOPOLOGICAL evidence of B's (and charm), and RECORDING them with our DAQ, we are open to all kinds of B physics – not just a specific "menu" that may be in vogue at any moment.

Pixel L1Trigger

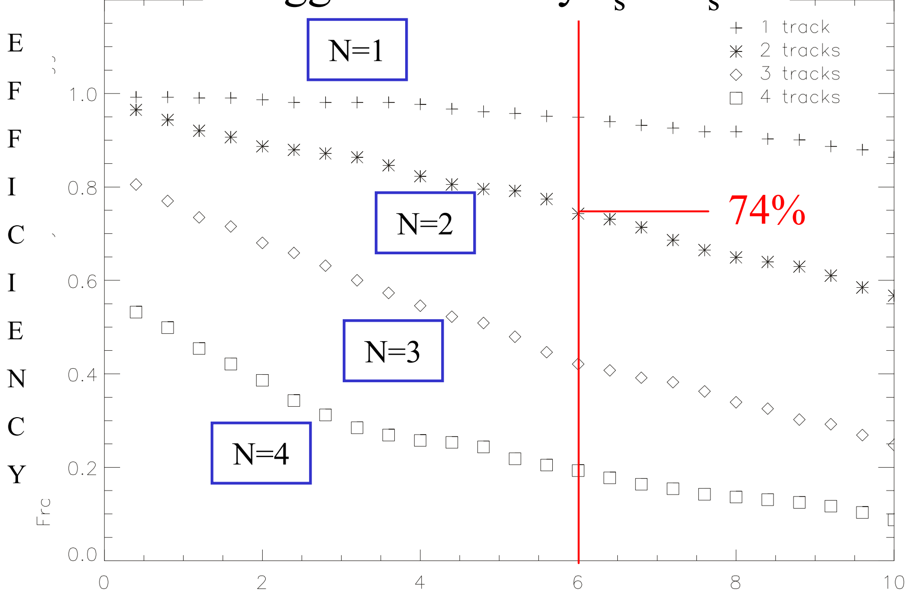
◆**Finds the primary vertex and identifies tracks which miss it, calculates the significance of detachment, b/σ(b).**



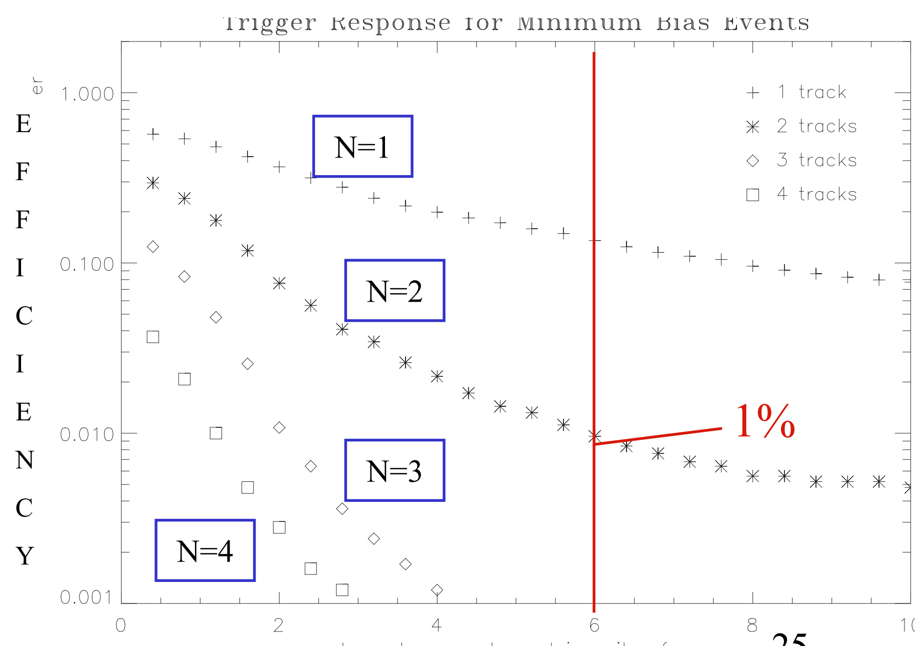
Process	Eff. (%)	Monte Carlo
Minimum bias	1	BTeVGeant
$B_s \to D_s^+ K^-$	74	BTeVGeant
$B^0 \to D^{*+}\rho^-$	64	BTeVGeant
$B^0 \to \rho^0\pi^0$	56	BTeVGeant
$B^0 \to J/\psi K_s$	50	BTeVGeant
$B_s \to J/\psi K^{*o}$	68	MCFast
$B^- \to D^0 K^-$	70	MCFast
$B^- \to K_s\pi^-$	27	MCFast
$B^0 \to$ 2-body modes $(\pi^+\pi^-, K^+\pi^-, K^+K^-)$	63	MCFast

Trigger Efficiency-Minimum Bias Events

Trigger Efficiency$B_s \to D_sK$

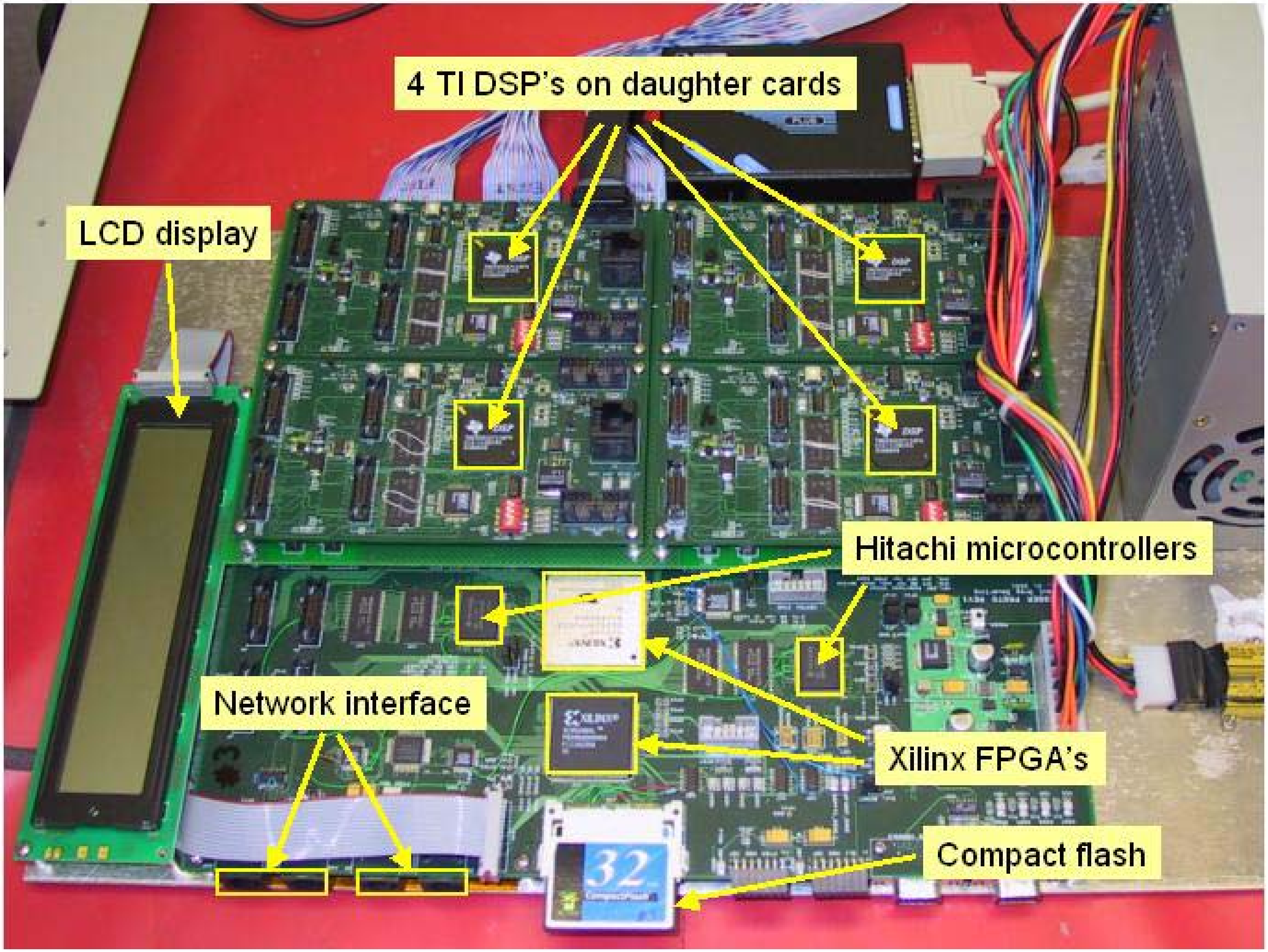


Impact Parameter in units of σ



Impact Parameter in units of σ

Prototype DSP Level 1 DSP Board



Fault Tolerance

- The trigger is working on many beam crossings at once. To achieve high utilization of all processors, it makes decisions as quickly as possible. There is no fixed latency and events are not emerging in the same time ordered sequence with which they enter the system.
- Keeping the trigger system going and being sure it is making the right decisions is a very demanding problem -- 6000-12,000 processing elements: FPGAs, DSPs. Commercial LINUX processors
- We have to write a lot of sophisticated fault tolerant, fault adaptive software
- **We are joined by a team of computer scientists who specialize in fault-tolerant computing under an award of $5M over 5 years from the US NSF**.

Vanderbilt, Syracuse, Illinois, Fermilab

Test Beam runs

- **Pixel – ready for second run with final readout chip**
- **Straws – ready for run to verify that it will hold up in high rate environment – well understood with cosmic ray test stand**
- **Strips – Tests at beginning of '04.**
- **RICH– ready for test beam in a few months – all parts designed and being assembled. Will test both HPD and MAPMT read out**
- **EMCAL – 4 test runs in Protvino completed– 5th in April. There will be a test beam setup at FNAL, mainly for quality assurance cross checks during production**
- **Muon– ready for second run, which will be final run before we are ready for production**

Project Organization

- We have an “interim” project management and project office
- Each Level 2 project has a group and a task leader
- Many Level 3 project leaders are also in place
- **These groups wrote the proposal and are carrying out the R&D program**
- We are organized to be able to complete our TDR –most of which already exists
- We are moving our WBS into OPEN PLAN and are beginning to see the first versions of the resource-loaded schedules for the project

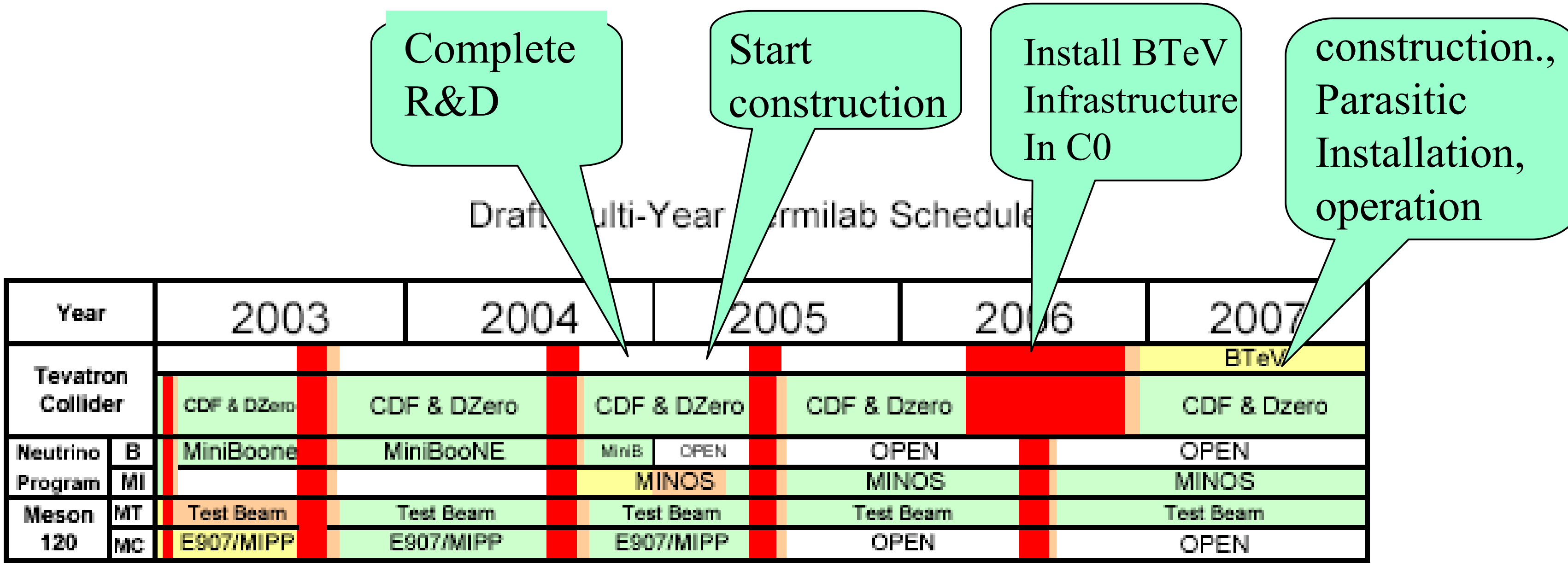
BTeV Cost Estimate

- Cost estimate is derived from a complete, task-oriented WBS. Realistic assumptions are made about the production model for each component. We have included integration activities in a complete and consistent manner
- Estimate starts in FY2004, when we “hopefully” become a construction project. IT IS IN FY2002 DOLLARS.
- Includes contingency-- 37.5%

Project Scheduling/Resource Loaded Schedule

- We are relying on OPEN PLAN scheduling software from WELCOM (COBRA)
- We have done one WBS -- Pixel 1.2 -- in Open Plan and believe it is a very good tool.
- Individual projects are largely decoupled, even at the installation level. Many items can be installed one piece at a time, even on short downtimes. This means that the critical path will not be so tightly coupled as it has been on central detectors.
- We have hand-loaded the cost and resource distributions that form the basis of the information we will be inputting

The Lab Schedule and BTeV



This draft schedule is meant to show the general outline of the Fermilab accelerator and experiments schedules.
Major components include:

- 6-8 week shutdown each summer
- 6-8 month shutdown for the installation of CDF and Dzero detector upgrades in 2006-7
- Startup of the NuMI operation with the MINOS detector

Additional shutdown periods will be added, typically allowing 40 weeks of accelerator operation per year .
The draft schedule will be updated as more precise information is made available .

RUN or DATA

STARTUP/COMMISSIONING

INSTALLATION

M&D (SHUTDOWN)

19-Mar-03

The Lab Schedule and BTeV

Construction, Parasitic installation, operation

Complete Construction, commission

Install IR

Commission and begin run

Draft Out-Years Fermilab Schedule

Year		2008	2009	2010	2011	2012
Tevatron Collider		BTeV	BTeV	BTeV	BTeV	BTeV
		CDF & DZero	CDF & DZero	OPEN	OPEN	OPEN
Neutrino Program	B	OPEN	OPEN	OPEN	OPEN	OPEN
	MI	MINOS	MINOS	OPEN	OPEN	OPEN
Meson 120	MT	Test Beam	Test Beam	Test Beam	Test Beam	Test Beam
	MC	E906	E906-DrellYan	E906-DrellYan	E906-DrellYan	OPEN
	ME/P	OPEN	CKM	CKM	CKM	CKM / OPEN

This draft schedule is meant to show the general outline of the Fermilab accelerator and experiments schedules.
Major components include:

- 6-8 week shutdown each summer.
- Startup of the BTeV experiment, including 3-month shutdown for low beta installation.
- Startup of the CKM experiment.
- Startup of the E906 experiment.

Additional shutdown periods will be added, typically allowing 40 weeks of accelerator operation per year.
The draft schedule will be updated as more precise information is made available, or projections change.

- RUN or DATA
- STARTUP/COMMISSIONING
- INSTALLATION
- M&D (SHUTDOWN)

19-Mar-03

Some Scheduling Details

- **Goal: complete the detector in calendar 2008 or early 2009**
- **Physical infrastructure** -analysis magnet, compensating dipoles, muon toroid, electromagnetic calorimeter support- installed **in '06 shutdown**
- Parasitic installation and commissioning begin in '07
- Trigger and DAQ will be completed last because it makes sense to wait on items whose price is falling with time
  - **07/08- we will have enough capacity for detector commissioning**
  - **End of 08 -We will have 50% of the full trigger and DAQ**
  - **We will complete the system in early 2009**
- Detector
  - **A 10% pixel system operational in 2006 and the full detector ready for installation in 2008**
  - **07/08 significant portions of the forward straws and microstrips**
  - **07/08 The RICH and Muon system fully assembled in 2007/8**
  - **We will have much of the EMCAL assembled in 2007, with completion in 2008**

Level 2 Cost Rollup

WBS #	WBS Activity Name	Construction (w.o. contingency) Million $ ('02)	Construction (with Contingency) Million $ ('02)
1	BTeV Construction	89.57	122.46
1.1	Vertex, Toroidal Magnet, Beam Pipe	1.34	1.88
1.2	Pixel Detector	11.80	17.08
1.3	RICH Detector	10.03	13.54
1.4	EM Calorimeter	11.30	14.51
1.5	Muon Detector	3.61	5.42
1.6	Forward Straw Tracker	5.93	8.36
1.7	Forward Silicon Microstrip Tracker	4.90	7.11
1.8	Trigger Electronics and Software	9.98	14.22
1.9	Event Readout and Controls	11.82	14.68
1.10	System Installation, Integration, etc	4.28	8.07
1.11	Project Management	6.46	7.43
	G&A estimate completion	8.14	10.18

Note: of the $89.6M base cost, 41% is labor, 59% is M&S. We estimate that inflation will result in a "then year" cost of $135 M

BTeV Resource Requirements

resource	Project Total (person-years)
Physicist (incl RA)	285
Graduate Student	53
Mechanical Engineer	44
Electronics Engineer and designers	108
Software Engineer	55
Senior Technician	36
Technician	110
Drafter	11

- Physics Manpower: for "construction" ~350 FTE-yr plus 200 FTE-yr for offline. Expected size of collaboration 250-350 x 5-6 yrs will be OK.
- Operating Costs: Estimated to be $4M/year, including CPU and disk additions and replacements
- Initial cost to FNAL for offline computing is $3M, assuming ~½ of all computing available through general university resources

Operation at 396 ns Bunch Crossing Interval

- BTeV was designed for $2x10^{32}$ at 132 ns, I.e. <2> interactions/crossing (initial) unleveled
- We now expect to run at $\sim 2x10^{32}$ at 396 ns, I.e.<6> int/crossing (initial) unleveled OR $\sim 1.3x10^{32}$ at 396, I.e. <4> int/crossing ,leveled
- To verify that we can do this, we have repeated many of our simulations but have run the code just as it was for two int/crossing– I.e. no retuning,so represents a worst case. We always used the peak rate, so our estimatesvhave been pessimistic. **Average impact across store is ~10%.**
- The key potential problems areas – trigger, Emcal, and RICH – all hold up well based on simulations

Will BTeV Be Timely? -- YES!

- **The character of this physics is that it unfolds gradually as statistics accumulate over a few years. Small differences in the starting time can be overcome by a superior detector. If we did start late w.r.t. LHCb, we have a better design and sufficient advantage in KEY states and would rapidly catch up, e.g. 4X better in ρ-π.**
- **We ARE a technologically superior experiment to LHCb due to the pixel detector, more inclusive trigger, and emcal and will collect a much larger sample of B's**
- **BTeV is designed so components can be installed on the fly a little at a time on collider down days.We can run low luminosity, 10^{30}, collisions at the end of stores or debug detectors on flux from a wire target in the beam halo. We can be commissioned before the final IR is complete. This is worth at least a half a year, if not more!**

Key Points

- **We have a technically sound, well-defined project scope that will accomplish our physics goals. The technical design has been stable for two years and has only a few options, which are ~equal in cost.**
- **We use commercial solutions or existing HEP solutions where possible.**
- **Our R&D program has gone a long way to reducing risks.**
- **The experiment has less "coupling" than hermetic central collider detectors, resulting in lower costs, uncertainties, ease of assembly and integration.**
- **Our cost estimate is quite complete and we are committed to modern and formal project management techniques.**

We are positioned to construct BTeV efficiently and to achieve the scope on schedule and within budget. The physics is great! We will do key measurements in B_s decays and states with γ's. Our ability to record all B states gives us the broadest possible scope and also makes us a great charm decay experiment.

Concluding Remarks

- BTeV will make critical contributions to our knowledge of CP Violation move from initial observations to finding out if the Standard Model explanation complete. BTeV is not just doing Standard Model physics. It can reveal new phenomena or help explain them
- BTeV makes excellent use of an existing DOMESTIC HEP facility in which there will have been a huge investment but doesn't overtax precious accelerator R&D resources
- The R&D projects are critical to developing the technologies that will make BTeV possible. The work will insure that it will succeed and will be done on schedule and on budget. The detector design has no show stoppers but we know that there are many challenges ahead of us.
- BTeV will form a key part of a world class domestic flavor physics program after the LHC takes firm possession of the energy frontier